EXPERIMENTAL TESTING OF THE SUPPORT SYSTEMS FOR PRECAST CONCRETE DOUBLE TEE FLOORING

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This paper presents the results of a research and development project looking at developing a practical solution for flange hung precast Tee units. A cost-effective design solution and associated design methodology was developed and subjected to experimental verification. All testing was completed using realistic boundary conditions and loading patterns to ensure the results were representative of the system when used in practice. The results highlighted potential issues with conventional precast concrete detailing, particularly the use of unreinforced ledges on the beams supporting the flooring units. These issues are discussed and practical, cost effective solutions are suggested for further refinement.

BACKGROUND

Over recent years the ability of precast concrete flooring systems to withstand imposed earthquake deformations and forces has been the focus of numerous research projects. Whilst initially concentrating on Hollow-core flooring, the most recently attention has been on the behaviour of flange hung Tee units.

The majority of support details for flange hung tee units have been developed for about 30 years. However, an increased understanding of concrete behaviour, an increased awareness of the importance of seismic drifts in building behaviour, and the behaviour of similar support details in overseas earthquakes, have lead the validity of a number of the support systems to be questioned.

The Structural Engineering Society of New Zealand (SESOC) has recently published findings from a research project into the behaviour of flange hung Tee unit support details, primarily focusing on the loop bar detail, sometimes known as the "pigtail" [S1].

The final recommendation from SESOC was that the loop bar detail be removed as a recommended system and that other validated systems be adopted instead.

EXPERIMENTAL PRODUCT VERIFICATION

AS/NZS 1170.0 has allowances for experimental testing to validate the performance of a system. It is intended that these requirements outdate any testing verification procedures in the materials standards. Any new products wishing to use experimental testing to validate the performance should ensure the testing programme complies with the requirements of this Standard.

Appendix A in AS/NZS 1170 provides guidance on the completion of special studies to "establish information or methods for design not given in this standard, or to define formation or methods used, or where more accuracy is considered necessary". Any testing undertaken for the special study is required to comply with the requirements of Appendix B of the standard.

Appendix B in AS/NZS 1170 defines two forms of product verification testing; Proof Testing of a structure or assembly, and Prototype Testing of a representative sample of a population.

Guidance is provides as to the requirements of the testing programme for both forms of product verification. However, when completing the development of a new product it is not typically feasible to undertake Prototype Testing, as the units are unlikely to have been produced in production quantities.

Detailed research programmes in New Zealand, such as University research programmes, have

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1 Managing Director, Holmes Solutions Ltd
typically used experimental testing as a means to validate and calibrate analytical models that have been derived to predict the behaviour of building element. This form of testing does not comply with the requirements of Appendix B of AS/NZS 1170.

However, it is internationally accepted practice that experimental testing be used as a means of calibrating analytical model, provided the model adequately describes the behaviour of the test specimen, predicts the failure mode, and is used to determine the point of failure (the failure load or displacement) of the test specimen. Experimental testing of this nature has been used as the basis of large portions of the material design Standards in New Zealand and internationally.

Any experimental testing programmes using this approach are required to meet strict criteria;

- The results from the testing must be used to calibrate a sound theoretical model used to predict the failure mechanism and failure point in the test specimen.
- The testing specimen must match the boundary conditions imposed in a real structure, and the test apparatus can neither help nor hindering the performance of the test specimen.
- The loading regime imposed should accurately matching the imposed actions, in both scale, timing, and sequence, that is imposed in the real structure.
- The testing programme should be peer reviewed by experienced parties, or be able to be replicated by an independent third party testing agency.
- The test reports must meet the reporting criteria imposed in AS/NZS 1170, include the evaluation and interpretation of the data.

This philosophy was applied when developing the testing regime used in this paper.

**ZEUS SYSTEM**

Stahlton Engineered Concrete developed an alternative flange hung support detail for double tee units, the Zeus system. The Zeus consists of a steel support bracket that is cast into the web of the Tee units. The bracket provides direct load transfer from the web of the units to the support beam ledger under both gravity and earthquake induced loads.

The Zeus system incorporates a life safety strap to ensure a backup load path exists between the flooring unit and the support beam. In the event of losing all seating from the support beam ledger, the life safety strap has sufficient capacity to provide gravity support for the unseated units, satisfying the requirements for life safety under a Maximum Credible Earthquake (MCE).

An experimental testing programme was developed to investigate the behaviour of the system under gravity loads, Design Basis Earthquakes (DBE) and MCE events.

Holmes Solutions were engaged as an independent third party testing agency. This paper provides a summary of the results from the testing. A detailed summary of the results is provided elsewhere [A1].

![Figure 1 Zeus Bracket](image)

**EXPERIMENTAL TESTING**

An experimental testing programme was developed by Holmes Solutions to satisfy the intent of AS/NZS 1170. The test specimens were designed to achieve similar boundary conditions to those of flooring units in buildings. A loading protocol was developed to simulate the actions imposed by gravity and earthquake loading.

Previous researchers have shown that two dimensional sub-assemblages can be used to accurately replicate the predominant damage caused in three dimensional building construction [J1, M1].

The testing programme was developed in two stages. Stage 1 investigated the behaviour of four test specimens when subjected to the imposed loading protocol. The results of Stage 1 were used to calibrate the theoretical design model for the Zeus system and if necessary, to complete any design modifications to the Zeus system. A further two test specimen are scheduled to be constructed and tested in stage 2 of the project.
Test set up

The behaviour of the Zeus support system was investigated using two dimensional sub-assemblage units, as detailed in Figure 2. The testing set up was established to correctly model the two most predominate damage causing mechanisms to the building elements when used in buildings subject to earthquake induced deformations, namely relative seating beam rotation and longitudinal beam elongation \[M1\].

The reduction from a full three dimensional assembly to two dimensional sub-assembly requires careful consideration of the boundary conditions and applied loads to ensure the correct behaviour is modelled. The sub-assembly is simulating the half span of a full floor unit with in-situ concrete topping built integrally with a supporting beam.

Additional gravity load is required to be applied to the sub-assembly in order to generate a shear gradient and vertical load on the seating support consistent with the equivalent full floor span system. A detailed description of the procedures used to determine the required gravity load of G+ Qo is provided elsewhere \[J1\].

Horizontal displacements were measured on the either side of the floor slab by using 100 mm travel linear potentiometers, mounted top surface of the floor slab.

All recorded load and displacement measurements were corrected for angle changes and load interactions on the actuators caused the displacements to the end of the floor slabs.

A series of potentiometers were used to record any relative movement of the support beam to the floor of the testing laboratory (translation and rotation) during the testing.

Loading Protocol

The primary purpose of the experimental testing was to evaluate the performance of the Zeus flange hung support system when subjected to gravity loads and earthquake induced deformations.

Jenson et al. \[J1\] developed an experimental drift history for a ductile frame building when subject to earthquake induced displacements. The loading protocol was based on experimental and analytical investigations completed by Matthews et al on a full scale three dimensional test specimen. The earthquake records used in the study were scaled to represent 10% chance of occurrence in 50 years (DBE) and 2% in 50 years (MCE).

The Jenson protocol is generally accepted as the industry standard for loading regimes that correctly simulate the applied actions from earthquake induced deformations, namely relative rotation between the floor unit and the support beam and longitudinal beam elongation. Fundamental to the protocol is the simultaneous application of the two displacements, thereby generating the potential for high forces on the end of the precast units and the support beams ledge due to the induced friction.

The loading patterns derived by Jenson, scaled according to the dimension of the test specimen, were used in this testing programme.

**Figure 2** Test Set up

Vertical loading was applied to the test unit via a hydraulic actuator located at the free end of the floor units. Vertical displacements were recorded by a rotary potentiometer located at the centroid height of the floor slab.

Horizontal displacements were induced into the floor units using a hydraulic actuator mounted on either side of the floor unit, at the centroid height of the floor slab. The hydraulic actuators attached to the floor slab via cast in weld plates approximately 2.5 m from the face of the supporting beam.

Horizontal displacements were measured on the either side of the floor slab by using 100 mm travel linear potentiometers, mounted top surface of the floor slab.
**Test Specimen Construction**

All test specimen were constructed using conventional manufacturing techniques as typically used in the construction industry.

The support beams were manufactured as precast “half” beams, produced from nominal 30 MPa concrete supplied by a local ready mix supplier. The supporting ledges of the units were finished using hand trowels to achieve a level of roughness typical in the construction industry, as detailed in Figure 4. It was felt that this would produce the highest potential for spalling of the support ledge of the beam and the highest tensile stresses in the support flanges and web of the flooring unit.

The supporting ledge of the support beam was unreinforced and had no armouring.

![Figure 4 Supporting ledge on the formed precast half beams](image)

The Single Tee floor units were manufactured by Stahlton Engineered Concrete in their Christchurch production facility. Strain gauges were fitted to the Zeus brackets and the adjacent steel (stirrups and strands) prior to pouring the concrete.

Two test units were fabricated with 200 mm deep Single Tee units and the remaining two were produced with 450 mm deep units.

A seating length of 75 mm was used for the Single Tee units. No bearing strips were used in the interface of the precast Tees and the supporting beams. This was considered the critical construction methodology for generating tensile stresses in the critical elements of the test specimen.

A life safety strap, manufactured from high tensile prestressing strand, was placed through the upper Zeus unit and laid on top of the support beam reinforcement. Strain gauges were attached to the life safety strap by brazing a thin steel strap to the strand.

![Figure 5 Construction of Test Unit 2](image)

A total of four XD12 reinforcing bars were placed as starter bars from the concrete support beam onto the floor slab. An XD12 is a 12 mm diameter deformed reinforcing bar with a lower characteristic yield strength of 500 MPa. The floor slab topping was reinforced with XD12 at 300 mm centres in each direction for the full length of the floor.

The floor units and top half of the precast support beams were poured using nominal 30 MPa conventional weight concrete supplied by a local ready mix supplier.

**TEST RESULTS**

The test units were cured in-situ for a minimum of 21 days prior to testing. On the day of testing all materials used in the specimen were tested to determine their material properties.

**Material Test Results**

The strengths obtained for the reinforcing steel and concrete used in the test specimen are shown below:

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Material Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Tee Depth (mm)</td>
</tr>
<tr>
<td>SP1</td>
<td>450</td>
</tr>
<tr>
<td>SP2</td>
<td>200</td>
</tr>
<tr>
<td>SP3</td>
<td>450</td>
</tr>
<tr>
<td>SP4</td>
<td>200</td>
</tr>
</tbody>
</table>

**Test Observations**

The following test observations are based on general observations across all test specimen.
Specific comments on individual test specimen are noted accordingly.

A visual inspection was completed on the test units prior to testing. No significant cracking was observed in any test specimen prior to the application of loads.

The additional dead load was installed onto the test units as two ballast blocks, weighing approximately 20 kN and 25 kN respectively. Once the blocks were installed, a series of cracks were observed in the topping concrete at the interface between the flooring units and the support beams. The crack was more pronounced in the test specimen with 200 mm thick Single Tee units.

During the first loading cycles to displacement rotation of 0.5%, the crack at the interface of the floor units and support beam became more pronounced. Under the reverse loading cycle minor cracks were observed to form on the underside of the floor unit, perpendicular to the length of the floor.

Cracking of the cover concrete on the support beam ledge was observed under the first cycle of loading to 1.0% drift. Different crack patterns, and extent of crack was observed for all test specimen, however the cracking was generally spread over the width of the floor units. This indicates that the flanges of the floor units, typically ignored in design calculations, were resisting a significant proportion of the apply loading.

During the reverse cycle of loading, to -1% drift, a number of the cracked concrete areas spalled from the face of the support beam. The largest area of spalling was observed in Test specimen SP3, with a 450 mm Tee depth.

The crack in the topping concrete at the interface of the flooring unit and support beam increased in width considerable during the loading cycles to ±1% drift. A series of parallel cracks also formed, on both sides of the original crack. Minor cracking was also observed around the cast-in weld plates supporting the axial extension actuators. However, this was significantly removed from the beam-to-floor interface so as not to interfere with the test observations.

Under the loading cycle to ±2.5% drift the XD12 starter bars fractured. All of the starter bars fractured in relatively quick succession. No additional cracks were observed to form in the topping concrete once the in the starter bars had fractured and the horizontal force required to generate the required extension displacements reduced considerably.
Under subsequent loading cycles, the primary crack at the interface of the floor and support beam grew in width, and additional spalling was observed on the ledge of the support beam.

Testing was stopped in all test specimen when the floor unit lost seating on one edge of the supporting ledge, typically causing the floor unit to rotate. The induced rotation made the support of the gravity load blocks unstable.

At the completion of the testing, the floor slabs were dragged off the supporting ledge until they had zero seating. In all test specimen, the life safety strap was effective in preventing the floor units from falling after they had lost the vertical seating support.

At the completion of the testing a detailed visual inspection was completed on the floor units. No discernable damage had occurred to webs. Cracking was observed in the flanges of two units, probably due to the high interface friction between the floor units and the supporting beams ledge.

**Experimental Results**

The experimental results obtained for Test specimen SP4 are shown in Figure 13. Test results for the other test specimen were similar, and are discussed in detail elsewhere [A1].

Test specimen SP4 achieved a maximum drift of 3.0%, exceeding the requirements for Design Basis Earthquake (DBE).

Testing was stopped due to lateral rotation of the flooring unit caused by the left hand flange of the flooring unit coming off the seating ledge of the supporting beam when the cover concrete spalled from the ledge. This resulted in the dead load ballast located on top of the floor slab becoming potentially unstable.

Figure 13 shows the elongation verse drift response, with the “walking” nature of the response, which is real buildings is caused by the elongation that occurs in the plastic hinges of the frames perpendicular to the supporting beam. When combined with the floor rotation relative to the supporting beam, the elongation of neighbouring beams is the fundamental influence causing friction on the ledge of the supporting beam, leading to the observed spalling.
Interface Friction

The force required to achieve the horizontal displacement targets was near identical for all four specimen. The maximum horizontal force resisted by each of the test specimen was 320 kN.

The axial strength of the four XD12 starter bars used in the test specimen was determined to be 242 kN, resulting in a residual force of approximately 90 kN. This force is comprised of the loads resisted by the life safety strap and friction component generated between the floor unit and the ledge of the supporting beam.

On average, the force in the two legged life safety strap was 36 kN, which when corrected for the angle of the legs results in a horizontal force of 30 kN. As a result, the average friction generated between the floor unit and the ledge of the support beam was 60 kN. This relates to a shear friction between the surfaces of 1.33. This is significantly higher than the value of 0.7 typically used in engineering design.

Support Ledge Spalling

All test specimens were observed to undergo significant spalling of the ledge of the support beam, as detailed in Figure 14. The spalling was typically spread across the flanges of the floor, with the greatest spalling occurring in the region of the web. This corresponds to the supporting region of the internal Zeus bracket.
NZS 3101 recommends ignoring the influence of the flanges of floor units when calculating the strength of the system. Whilst this provides a conservative estimate of the systems strength, it may lead to an under estimation of the stresses imposed on the edge of the supporting edge.

Based on the results obtained from the four experimental tests it is believed that the spalling could have been prevented by ensuring the support of the floor unit was set back from the edge of the supporting beam ledge, using a low friction bearing strip (as recommended by NZS 3101), and armouring the edge of the supporting ledge.

Whilst the testing conducted in this experimental programme was limited to the behaviour of the Zeus system, it is believed that the findings related to the spalling of the support details are equally relevant to other flange hung support systems.

Life Safety Straps

The life safety straps used in the Zeus system were successful at supporting the floor units under full gravity load after the units had lost all support from the ledge of the supporting beam.

Strains in the life safety straps typically remained low through out the testing, indicating that they were out of the primary load path during load cycles up to and exceeding 2.5% drift. This indicates that they had sufficient reserve capacity to resist the loads imposed under full gravity support.

The results from the experimental testing indicate that the life safety straps are an effective means of achieving life safety in a building under the Maximum Credible Earthquake (MCE).

The behaviour of the life safety straps could be improved by reducing the lateral spread of the legs, making them more effective in the longitudinal direction, and by undertaking debonding along a portion of their length to prevent locations of high strain concentrations.

Zeus Support System

The Zeus system performed well under the experimental testing. The internal steel bracket was successful in supporting the web of the floor Tee and transferring the loads to the ledge of the support beam. No cracking was observed in the webs of any test specimen.

The results obtained for all four test specimen were very consistent, indicating that the system behaves in a predictable and consistent manner.

All four test specimen achieved at least one cycle to drift of 2.5% before testing was stopped. NZS 3101 requires that buildings have sufficient ductility to achieve a minimum of four cycles of loading to deflections exceeding drifts of 2.5% under the Design Basis Earthquake (DBE).

The life safety straps were found to be successful at providing gravity support of the floor units at the end of the testing regime, exceeding the life safety requirements for MCE earthquakes.

The overall performance of the system was limited by the friction forces generated between the ledge of the support beam and the underside of the floor unit, resulting in premature spalling of the ledge and a loss of support to the flooring units. The behaviour of the system would be significantly improved using armoured edges to the supporting ledges or the use of ultra low friction bearing strips that are located back from the edge of the ledges.

Given the consistency of the test results for the Stage 1 test specimen it is proposed to use a single test specimen design for the Stage 2 experimental testing, comprising of 450 mm deep Tee units.
The experimental testing programme described above was Stage 1 of the Zeus testing programme. The results of the testing programme were used to refine the design of the system before Stage 2 testing was completed.

The shape of the Zeus system was refined to reduce the potential for stress concentrations on the supporting beam ledge, as shown in Figure 16. The rounded back edge allows the system to undergo a higher degree of building drift whilst maintaining a solid bearing surface.

Figure 16  Refined Zeus Bracket Shape

The shape of the internal leg was also modified to include a greater bearing area so that the compressive strut develops and decreases stresses at the node point, and for a more direct load path to the tension tie.

The shape of the life safety straps have been refined to provide a greater debonded length, and more angled legs thereby forming a more direct load path to resist the loads caused by the induced horizontal displacements.

The seating details with the support edge are being modified, with the potential to include an ultra low friction bearing strip set back for the edge of the support beam and an armoured edge to the support beam.

CONCLUSIONS

An experimental testing programme was completed on the Zeus system, a flange hung support detail for Tee flooring units.

The flooring units were constructed into test specimens using realistic boundary conditions and subjected to simulated earthquake and gravity loading, applied in accordance to strict testing protocol.

The conclusions from the testing programme included:

- All test specimen behaved in a similar manner, achieving near identical peak loads and failure modes. There was no significant variation in behaviour between the 200 mm and 450 mm deep Tee units.
- The coefficient of friction between the underside of the floor units and the supporting ledge was calculated to be 1.33.
- Extensive spalling was observed to the edge of the support beam under all test specimens, ultimately resulting in the loss of support to the floor units.
- Significant spalling was observed under the flanges of the floor units. Conventional engineering design ignores the influence of the flanges in the behaviour of the system. Whilst this approach is conservative for determining the strength of the system it may lead to unacceptable level of damage to the building elements and result in unforeseen failure modes.
- Armouring the edges of the support beam (or significantly limiting the friction) would have significantly improved the behaviour of the system.
- Damage to the test specimen was limited to cracking at the interface of the concrete floor units and supporting beam.
- All starter bars fractured during the testing.
- The life safety strap proved effective at maintaining the gravity load support of the floors after the seating had been compromised. This system could be used to satisfy the MCE requirements of life safety in buildings.

References


